Lateral Inflow into High-Velocity Channels

by Richard L. Stockstill

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) investigates lateral flow discharging into a high-velocity channel. The results of a series of laboratory and numerical model experiments are presented. Various geometric and hydraulic conditions were studied to evaluate hydraulic variables such as location and magnitude of peak depths. This depth information is necessary for determination of channel wall heights required to contain flows in the vicinity of laterals.

BACKGROUND: A previous study identified features common to high-velocity channels for which hydraulic design guidance is limited (Stockstill 2006). The study showed that the design guidance for confluences of supercritical flow needs improvement. Hydraulic design guidance of high-velocity channels at trapezoidal-channel confluences and storm-drain laterals is not complete. The current study addresses the case where culvert flow is introduced into the main channel in a lateral. The storm-drain flow is typically introduced as a circular pipe having a flap gate (to prevent backflow) as shown in Figure 1. High-velocity channel design allows laterals if the culvert flow is less than 10 percent of the main-channel flow. If the tributary flow is larger than 10 percent of the main-channel flow rate, the construction of an open-channel confluence (rather than a lateral pipe inflow) is recommended by Engineer Manual 1110-2-1601 (Headquarters, U.S. Army Corps of Engineers 1991). Confluences of supercritical flow are complicated by the fact that standing waves are generated at any and all boundary alignment changes. Photographs of high-velocity-channel flow at a lateral are provided in Figure 2. The pictures show the water-surface bulking due to lateral inflow.

This technical note summarizes the results reported in Stockstill (2007), wherein data from different physical models was supplemented with the results from a validated two-dimensional (2-D) numerical model. Various geometric and hydraulic conditions were studied in order to evaluate the head loss across a lateral and the hydraulic conditions such as location and magnitude of peak depths. Knowledge of these flow conditions is necessary for hydraulic design of channel walls (height and length) required to contain flows in the vicinity of laterals. The information is obtained from a physical model and supplemented with numerical model results. Additional data were obtained from the U.S. Army Engineer District, Los Angeles (1960) report and physical model studies of the Walnut Creek Channel (U.S. Army Engineer District, Los Angeles, 1964) and the Hoosic River Flood-Control Channel (U.S. Army Engineer Waterways Experiment Station 1962). These physical models provide only a few data points, but data from studies of lateral inflows are limited. The results of various physical models are supplemented with numerical model results to quantify the local depth increases and energy losses associated with lateral inflow.

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Figure 1. Lateral inflow pipe with flap gate.

Figure 2. Photograph of standing waves associated with lateral inflows.

GOVERNING PARAMETERS: Primary geometric and flow variables found at a lateral junction in an urban channel are shown in Figure 3. Given the flow conditions upstream of the lateral, depth (h_1), width (b), and discharge (Q_1) and the lateral particulars, the pipe diameter (d), submergence (S), and discharge (Q_2), then the important geometric and hydraulic parameters associated with lateral inflow are as follows:

$$\text{Upstream Froude number} = Fr_1 = \frac{V_1}{\sqrt{gh_1}}$$

$$\text{Discharge ratio} = \frac{Q_2}{Q_1}$$

$$\text{Width of channel to channel depth ratio} = \frac{b}{h_1}$$

$$\text{Pipe diameter to channel depth ratio} = \frac{d}{h_1}$$

$$\text{Submergence to channel depth ratio} = \frac{S}{h_1}$$

Data were gathered and analyzed to determine the significance of each of these parameters.
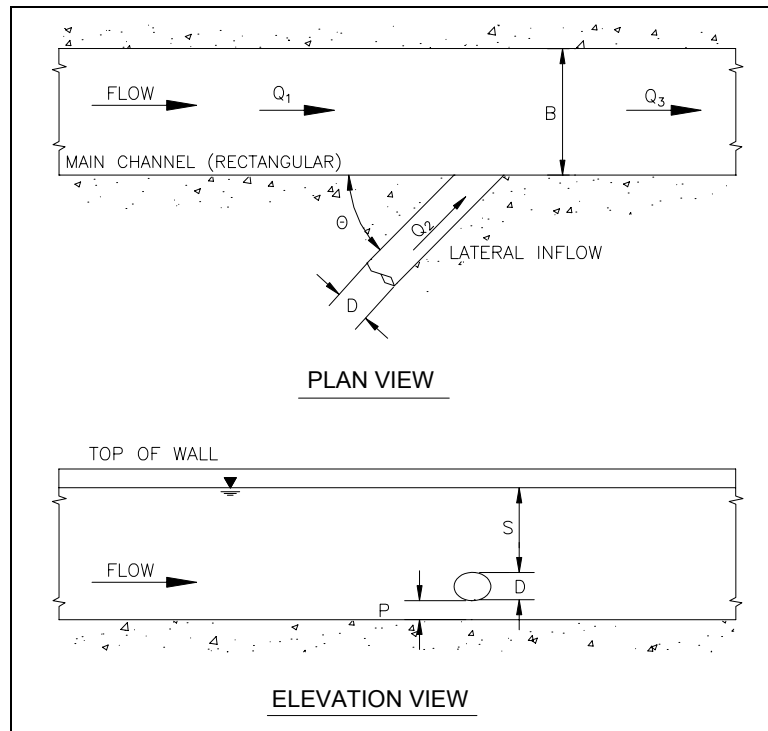

Figure 3. Layout of lateral inflow into main channel.

ENERGY LOSS: The difference in the energy upstream and downstream is the energy loss due to the flow disturbance caused by the lateral inflow. This energy loss can be expressed in terms of the upstream velocity head with a loss coefficient, K, as:

$$\Delta E = K \frac{V_1^2}{2g} \tag{1}$$

Values of K were determined using computer simulations of various angles and discharge ratios. A graph showing the variation of K for lateral discharge to main-channel discharge ratios of 0.01, 0.05, and 0.10 and lateral angles of 30 deg and 60 deg is shown in Figure 4. Laterals at angles of 90 deg choked the flow and, thus, energy losses were difficult to establish since the resulting hydraulic jump often migrated to the upstream model limit. The results suggest that a lateral angle of 60 deg results in less head loss than an angle of 30 deg. This apparent logical discrepancy is attributed to the fact that the energy supplied to the system by the lateral was ignored in the definition of the loss coefficient, K. Generalization of the results in Figure 4 indicates that a loss coefficient of 0.7 is a reasonable estimate for computation of head loss for the conditions examined.
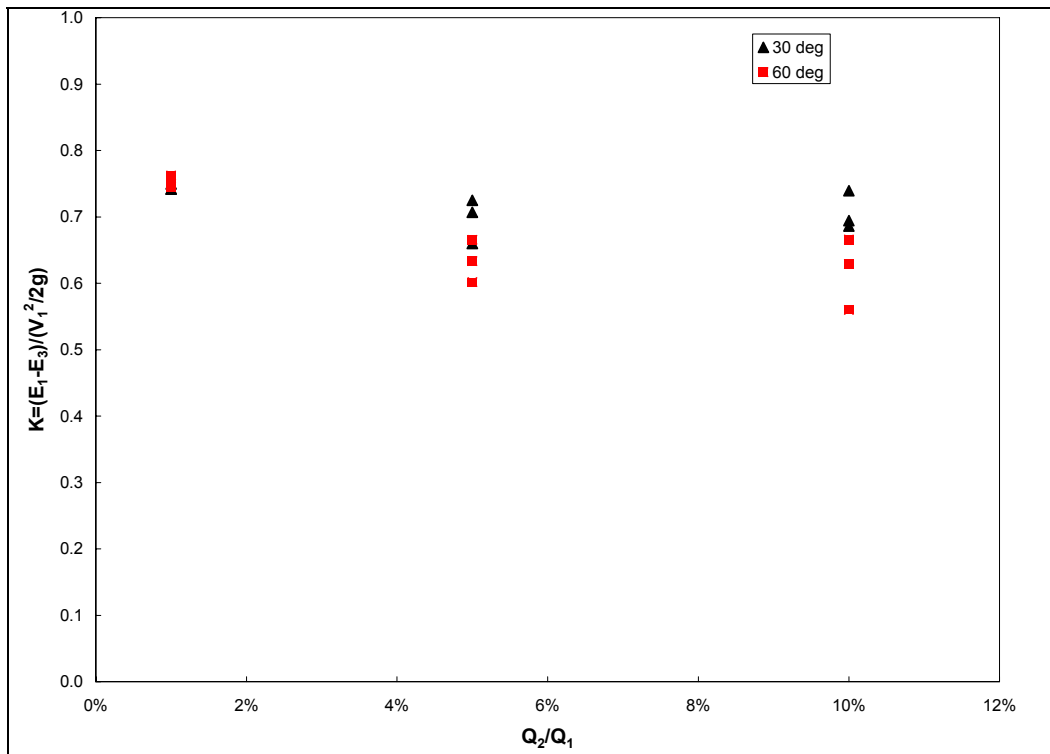

Figure 4. Energy loss coefficient for flow past a lateral.

OBLIQUE STANDING WAVES: When the flow is supercritical, oblique standing waves are generated at the lateral, and the local depth can be significantly larger than normal depth. As the supercritical flow in the main channel is disturbed by the flow issuing from the lateral, an oblique standing wave can be generated. A sketch of the wave pattern is provided in Figure 5. Even if there is no discharge from the lateral, the wall discontinuity at the lateral generates an oblique standing wave. Ippen (1951) shows that if only the disturbance point at the lateral intersection with the channel wall is considered (i.e., ignoring the flow from the lateral), then the angle is simply a function of the approaching Froude number.
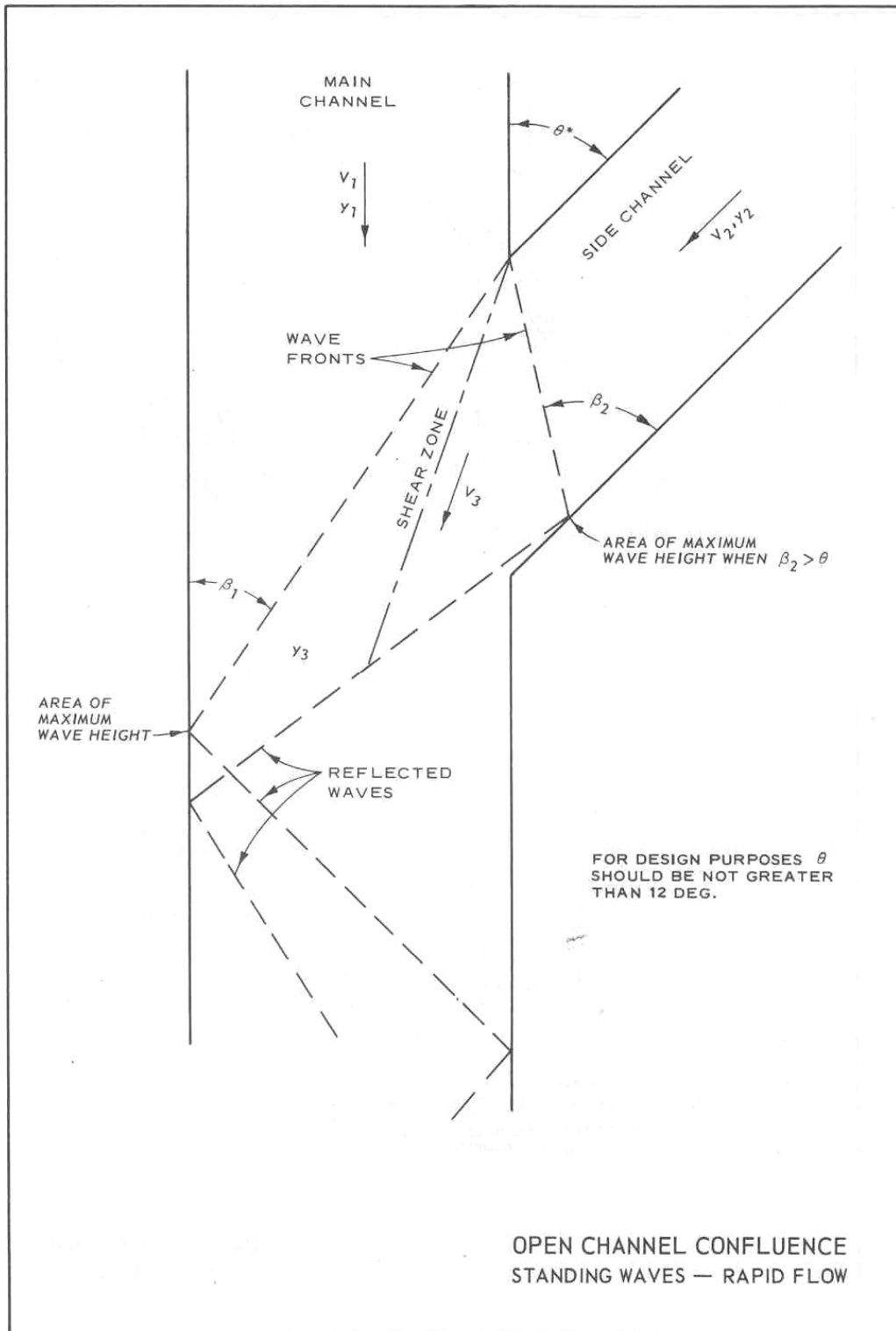
MAIN
CHANNEL

θ^*

V_1
y_1

SIDE CHANNEL

V_2, y_2

WAVE
FRONTS

β_2

SHEAR ZONE

V_3

AREA OF MAXIMUM
WAVE HEIGHT WHEN $\beta_2 > \theta$

β_1

y_3

AREA OF
MAXIMUM
WAVE HEIGHT

REFLECTED
WAVES

FOR DESIGN PURPOSES θ
SHOULD BE NOT GREATER
THAN 12 DEG.

OPEN CHANNEL CONFLUENCE
STANDING WAVES — RAPID FLOW

Figure 5. Plate B-53 from EM 1110-2-1601.

$$\beta = \sin\left(\frac{1}{Fr_1}\right) \tag{2}$$

This relation is developed assuming the flow is hydrostatic and that bed friction is negligible.

The concern here is the peak depth, which occurs at the intersection of the standing wave and the channel wall opposite the lateral. The peak occurs at a distance downstream from the lateral, L, and across the channel of width, b (Figure 6). The peak depth occurs at the nondimensional distance, L/b, downstream from the lateral. If the lateral flow is ignored, Equation 2 shows that this location is only dependent on the approaching Froude number as:

$$\frac{L}{b} = \sqrt{Fr_1^2 - 1} \tag{3}$$

Actually, since the flow from the lateral alters the standing wave angle and the pressure is not hydrostatic in the vicinity of the wave, it is expected that the observed peak depth along the wall opposite the lateral will vary from the theoretical angle.
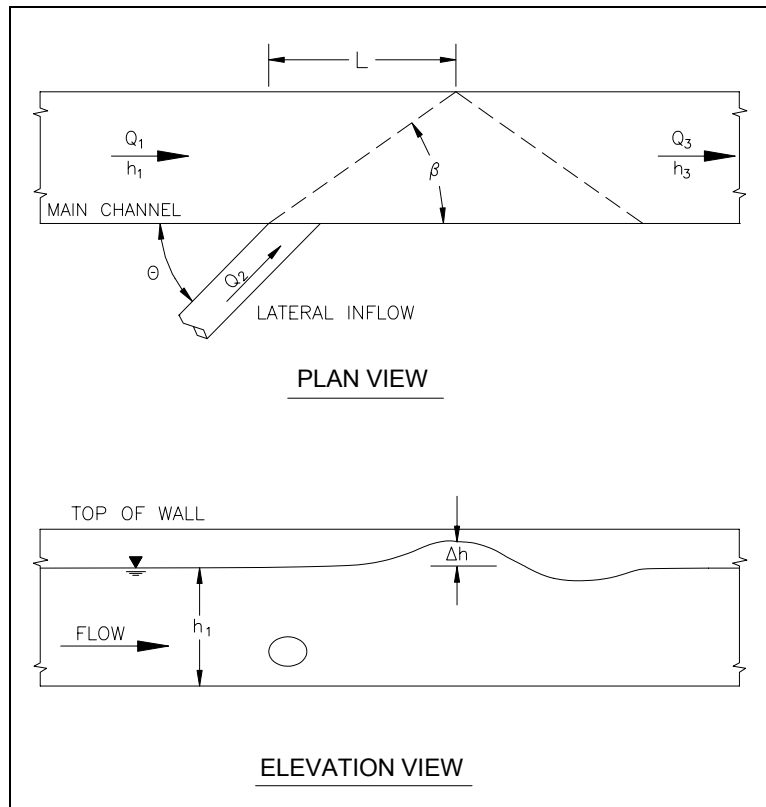

Figure 6. Peak depth location.

CHOKE: The choked flow condition is defined as the case where the lateral flow creates enough energy loss in the main-channel flow that a hydraulic jump is formed. This transition from supercritical flow to subcritical flow usually occurs in an undular jump forming upstream of the lateral. The undular jump is characterized by a series of standing waves occurring over a relatively long reach of the channel. The flow depths of the resulting subcritical flow are significantly larger than normal flow depths. Both the required wall height and wall length definitely increase for a choked flow condition.

PEAK DEPTH: Momentum in the main channel has a substantial effect on the path that the issuing jet makes as it mixes with the channel flow. The location of peak depth is presented from the various data sources in a dimensionless form, L/b as shown in the data presented in Figure 7. The theoretical curve in Figure 7 is Equation 3. Those data values at L/b equal to zero are associated with choked flow conditions where no oblique standing waves exist. The magnitudes of the peak depth are plotted relative to the discharge ratio, Q_1/Q_2 in Figure 8 and relative to the lateral angle in Figure 9. The plot shows that the peak depth varies significantly as the flow ratio increases. Values of peak depth vary the most for a ratio of 10 percent where the change in depth, Δh, can be greater than 2 times larger than the downstream normal depth, h_3. The largest depths are associated with the lateral angle of 90 deg wherein the flow is choked.
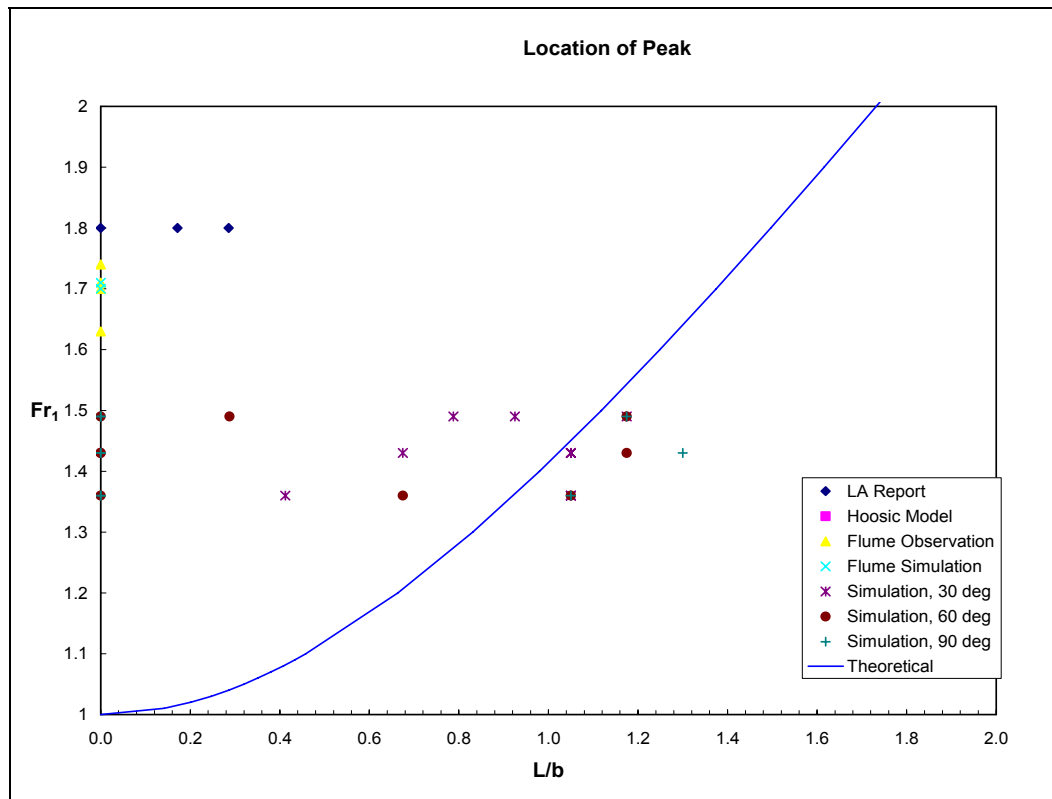

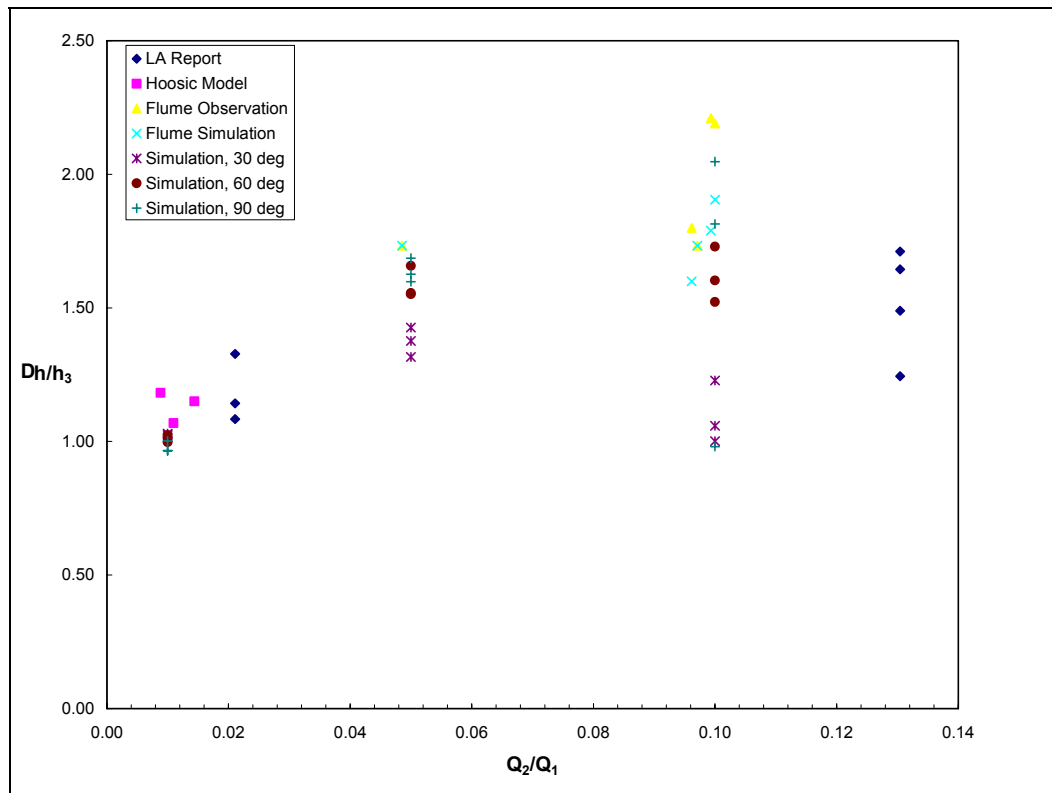Figure 7. Location of peak depth as a function of upstream Froude number.

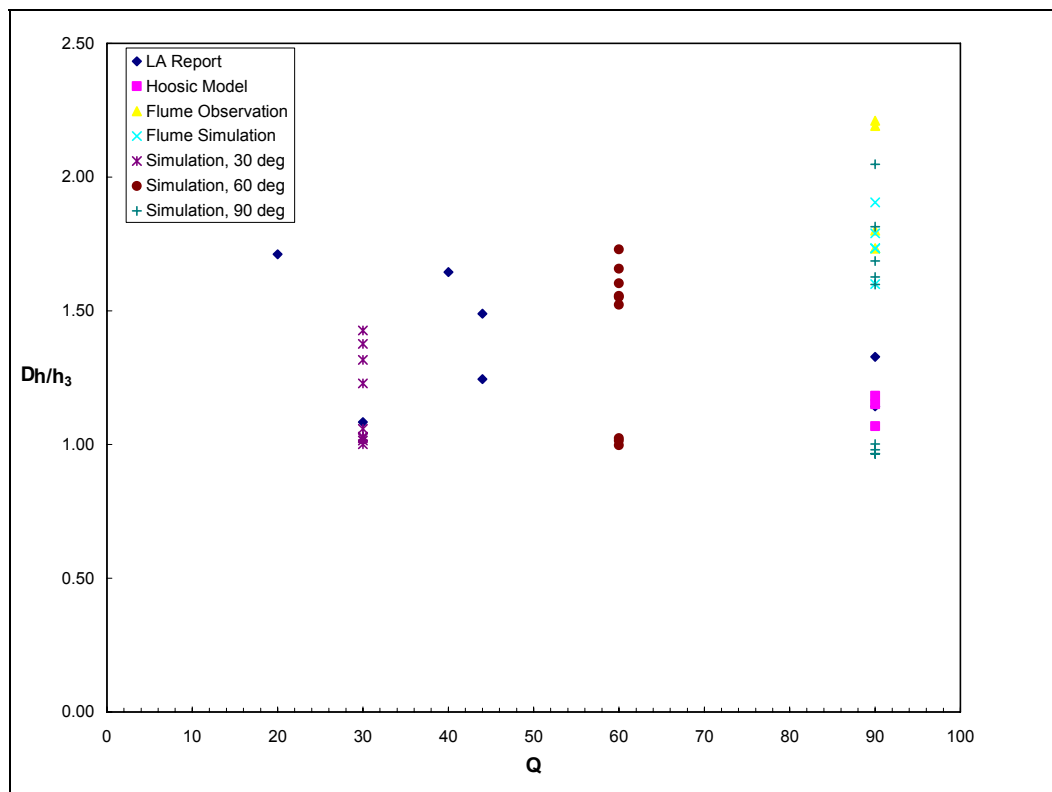Figure 8. Peak depth as a function of flow ratio.

Figure 9. Peak depth as a function of lateral angle.

Another important consideration regards the extent of oblique waves downstream from the lateral. The disturbance will affect flow patterns at features such as bends and confluences downstream of the lateral. Also, the distance required to return to near normal depth is key to designing wall heights. The laboratory data suggest that a distance of at least 10 channel widths is required to reestablish relatively smooth flow downstream from the lateral.

SUMMARY: This study has investigated lateral flow introduced into rectangular man-made channels designed to convey supercritical flow. A series of laboratory experiments and numerical model results were presented. Various geometric and hydraulic conditions were studied to evaluate hydraulic variables such as location and magnitude of peak depths. This depth information is necessary for determination of channel wall heights required to contain flows in the vicinity of laterals.

The head loss experienced by the main-channel flow as it crosses lateral inflow, Equation 1, can be estimated using a loss coefficient 0.7. This coefficient is an average value for all lateral angles and discharge ratios examined. Oblique standing waves are generated at a lateral when the flow is supercritical. The local depth in this wave pattern can be significantly larger than normal depth. A lateral angle of 90 deg produced choked flow for each of the conditions studied. Smaller values of lateral angle produce less depth increase. Data from laboratory experiments suggest that a distance of at least 10 channel widths is required to reestablish relatively smooth flow downstream from a lateral.

FUTURE WORK: A systematic flume study must be conducted to evaluate and quantify the effects of each of the governing parameters. Such a laboratory study was beyond the scope of the current project. However, since the parameters and flow mechanics have been established, a laboratory study should prove to be valuable. The effects of submergence, discharge ratio, channel width, and lateral angle can be quantified with experiments.

POINT OF CONTACT: For additional information, contact Dr. Richard L. Stockstill, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180, (601) 634-4251, email: Richard.L.Stockstill@erdc.usace.army.mil. This technical note should be cited as follows:

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